MS7460 Polymer Recycling and Sustainable Polymeric Materials

Rationale

The topic of polymer recycling and sustainable materials has rapidly evolved and has become extremely relevant for (PhD and Meng) students of the School of Materials Science and Engineering. In the first halve of the course we will look at existing materials and how to recycle them. After a recapitulation of the synthesis and composition of some of the main materials, we will cover primary recycling (within the materials manufacturing site), secondary recycling/mechanical recycling, tertiary/chemical recycling to polymer building blocks or other valuable materials. Also quaternary recycling (energy recovery or compostable materials) will be covered. Central at polymer recycling stands collecting and sorting. We will briefly touch upon issues with materials winding up in the environment.

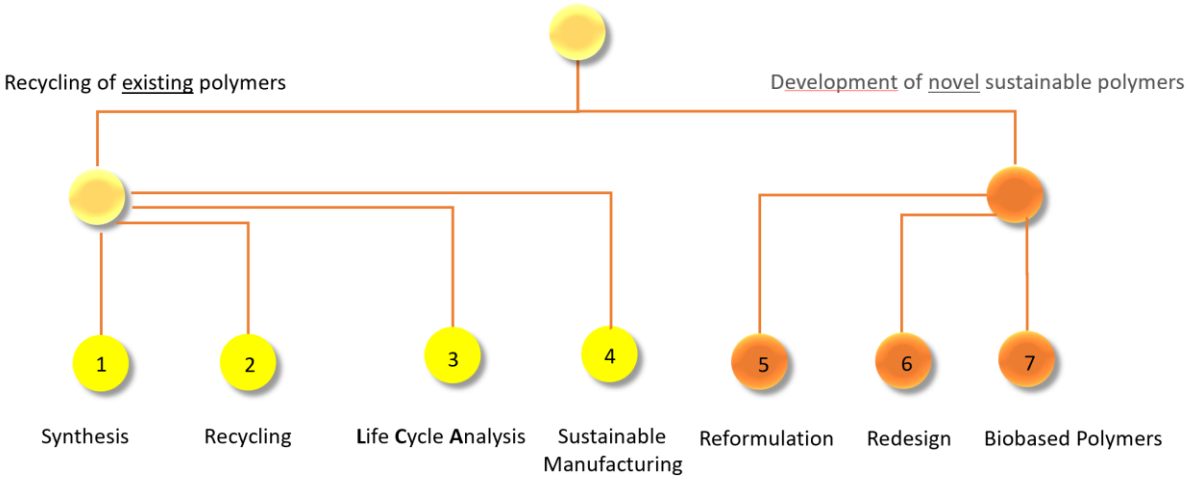
In the second halve we will cover in detail the scientific field of materials science and the methods required for the development of novel sustainable materials. Some aspects of sustainable manufacturing of materials will be shown (*eg* emulsion polymerization). An introduction to life cycle analysis (LCA) of materials will be given. Then we cover reformulation of materials; for example towards mono-materials and reduction of certain additives (for example colorants). Redesigning polymer materials on a molecular level to make them more easily recyclable through for example the thermoplastic elastomer approach or by introducing dynamic crosslinks (vitrimers) will be extensively covered. Introduction of weak bonds to be able to break down high molecular weight polymers into reactive oligomers is a new and exciting area which will also be covered. Briefly we will touch upon alternative (biobased) building blocks for materials as well as biobased materials replacement. We will review relevant scientific literature on the subject related to several crucial scientific fields and the individual fields of interest of the students with practical cases and lively discussions. The students will write an essay where the main elements of the course will be applied to a topic of their individual choice in the area of sustainable materials.

(A) Course "*Polymer Recycling and Sustainable Polymeric Materials*"

Total No. of Hours				AU
Lecture	**Tutorial**	**Lab**	**Total**	
17	9	-	26	2

Further details on course (e.g. course aims, intended learning outcomes, course content, assessment, etc) are provided in **Annex A**.

Polymer Recycling and Sustainable Polymeric Materials



Annex A

1. COURSE CONTENT

Course Coordinator	Professor Alex van Herk
Course Code	MS7460
Course Title	Polymer Recycling and Sustainable Polymeric Materials
Pre-requisites	NA
No of AUs	2
Contact Hours	26 (17 lecture hours and 9 tutorial hours)
Suggested Class Size	30

Course Aims
1 This course is trying to achieve full awareness of the sustainability aspects of materials. This includes looking at existing materials and their ways of recycling as well as redesigning materials on formulation and molecular level. 2 The course should be taken by PhD and MEng in Materials Science and Engineering and MSc in Materials Science and Engineering that have a vested interest in sustainability of polymer materials. 3 Any professional in materials will be looking at sustainability aspects of materials, being it facilitating recycling or replacement by more sustainable alternatives. So for a future career in materials (being it in research or industry) this course is very useful.

Intended Learning Outcomes (ILO)

By the end of this course, you should be able to:

1 explain the important aspects of the polymerization mechanisms of materials
2 classify the main materials according to key materials properties and polymerization mechanism of formation
3 identify the main environmental issues with polymer waste
4 identify the most important aspects of polymer waste collection and sorting
5 explain the main aspects and current industrial applications of the four polymer recycling routes
6 explain the main aspects of life cycle analysis
7 give examples of aspects of sustainable manufacturing of materials
8 to apply aspects of reformulation of materials to make then more sustainable
9 to apply aspects of redesigning materials on a molecular level to make them more sustainable
10 to explain the main biobased building blocks and biobased replacements of materials
11 critically read and interpret scientific literature in the area of sustainable polymeric materials
12 write an essay in your specific area of interest with respect to sustainable polymeric materials

Course Content

Materials classification
Key materials properties
Step-growth polymerization
Chain-growth polymerization
Polymerization techniques
Environmental issues
Collecting and sorting of materials
Primary recycling
Secondary/mechanical recycling with deterioration of properties and remedies
Tertiary/chemical recycling
Quaternary recycling (energy recovery and/or compostable materials)
Life Cycle Analysis
Aspects of sustainable manufacturing of materials (eg emulsion polymerization)
Reformulation of materials for increased sustainability
-Monomaterials
-Additives
Redesign of materials on molecular level

-Thermoplastic vs thermoharders;
physical crosslinks (thermoplastic elastomers), reversible crosslinks (vitrimers)
-Insertion of weak bonds
Biobased building blocks
Biobased materials replacements
Discussion of scientific literature on sustainable materials
Essay writing on sustainable materials

Assessment (includes both continuous and summative assessment)

Component	**ILO Tested**	**Weighting**	**Team/Individual**	**Assessment Rubrics**
1. *Quizzes (6)*	*1-10*	*60%*	*Individual*	*Appendix 1*
2. *Continuous Assessment and class participation during live sessions (6)*	*1-11*	*20%*	*Individual*	*Appendix 2*
3.Essay	*12*	*20%*	*Individual*	*Appendix 3*
Total		100%		

Formative feedback

Every session we will discuss the answers of the previous quiz. Your final essay will be graded and comments from me and your peers will be given.

Learning and Teaching Approach

Approach	How does this approach support you in achieving the learning outcomes?
Lecture (prerecorded)	*The lecture materials are accompanied by self-practice questions, not only help to build the fundamental technical knowledge required for this course, but also help to develop your individual learning abilities and attitudes toward active learning. You may attempt the self-practice questions anytime, anywhere, and you can revisit the self-practice questions as many times as you want.*
Live (on-line sessions)	*These sessions will allow you to ask specific questions and for the teacher to assess you understanding of the course materials. We will discuss scientific literature in the area of sustainable materials.*
Essay writing	*This will allow the technical knowledge acquired in this course to be applied to a topic of specific interest to the student and apply design principles from the course. Some specific questions about your essay will be asked after submission. These questions serve to establish to what extend you are "owning" the essay.*

Reading and References

Introductory reading:

For basics in polymer chemistry (ILO 1,2): for example *Introduction to Polymers*
By Robert J. Young, Peter A. Lovell, chapters 1-4 **or** M. P. Stevens, *Polymer Chemistry, An Introduction*, chapters 1-4.
0 Straights Times Nov 2, 2019 *Biodegradable disposables can harm environment too*
1 Nature 2021 Vol 590, p423, *Closed-loop recycling of polyethylene-like materials*, S. Mecking et al.
2 Nature Reviews *2022 2:46, Sustainable Polymers,* Amar K. Mohanty et al.

Further reading and some of the papers to be discussed in the live sessions (number in bold):
3 Science 2021, Vol. 373, No. 6550 *Plastics In The Earth System*. ,A. Stubbings Et Al.
4 Macromol. Rapid Commun. 2021, 42, 2000415, *Mechanical Recycling of Packaging Plastics, A Review*, Z.O.G. Schijns, M.P. Shaver
5 Nature Reviews, Materials https://doi.org/10.1038/s41578-020-0190-4*, Chemical Recycling to monomer for an ideal, circular polymer economy*, G.W. Coates and Y.D.Y.L. Getzler.
6 Waste Management 104 (2020) 148–182 Challenges and opportunities of solvent-based additive extraction methods for plastic recycling, Sibel Ügdüler et al.
7 Recycling 2022, 7, 11, *Assessment of performance and challenges in use of commercial automated sorting technology for plastic waste*., C. Lubongo and P. Alexandridis
8 www.Intechopen.com 2012 *Recent Advances in the Chemical Recycling of Polymers*, D.S. Achilias et al.
9 *Sci. Adv.* 2020; 6 : eaba7599, *Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation* , Walker *et al*.,
10 Grün Book – *CLOSING THE WASTE LOOP THROUGH INNOVATIVE PLASTIC RECYCLING 2020*
11 Environ. Sci. Technol. 2010, 44, 8264-8269. *Sustainability Metrics: Life Cycle Assessment and Green Design in Polymers*, M.D. Tabone et al.
12 J. of Industrial Ecology 2021, 25, 1318-1337 *Techno-economic assessment and comparison of different plastic recycling pathways*, R. Volk et al.
13 Waste Management 105 (2020) 128-138 *Technologies for chemical recycling of household plastics-A technical review and TRL assessment*, M. Solis, S. Silveria
14 Resources, Conservation and Recycling Vol 145, 2019, p 67-77, *LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore*, Hsien H. Khoo
15 Macromol. Chem. Phys. 2022, *223*, 2100488 *The Frontier of Plastics Recycling: Rethinking Waste as a Resource for High-Value Applications* Hannah Mangold et al.
16 Macromol. Chem. Phys. 2022, *223*, 2200111 *Getting the Terms Right: Green, Sustainable, or Circular Chemistry?,* Hatice Mutlu and Leonie Barner

17 Canadian Journal of Chemical Engineering, 2021, vol 99, p 31–60.Sustainable polymer reaction engineering: Are we there yet?, M. Dube et al.
18 Resources, Conservation & Recycling 179 (2022) 106126 *Recyclable-by-design mono-material flexible packaging with high barrier properties realized through graphene hybrid coatings* Marco Guerritore et al.
19 Angew. Chem. 2024, 136, e202402436 Photocatalytic Upcycling and Depolymerization of Vinyl Polymers Kostas Parkatzidis, Hyun Suk Wang, and Athina Anastasaki
20 Macromolecules **53**, 3994-4011 (2020). *Degradable Poly(alkyl acrylates) with Uniform Insertion of Ester Bonds, Comparing Batch and Semibatch Copolymerizations*, Lena et al.
21 J. Am. Chem. Soc. *2020, 142, 2100−2104 A Polymer with "Locked" Degradability: Superior Backbone Stability and Accessible Degradability Enabled by Mechanophore Installation*, Hsu et al.
22 Science 334, 965 (2011, *Silica-like malleable materials from permanent organic networks*. L. Leibler et al.
23 www.bio-based.eu/markets *Bio-based Building Blocks and Polymers in the World*, Pia Skoczinski, et al. Edition 2020
24 Procedia CIRP 116 (2023) 522–527 *Life Cycle Assessment of Plastic Waste End-of-life Treatments in Singapore* . Jonathan Low et al

Course Policies and Student Responsibilities

(1) General

You are expected to complete all assigned pre-class (live sessions) readings and activities, attend all live sessions punctually and take all scheduled assignments and quizes by due dates. You are

expected to take responsibility to follow up with course notes, assignments and course related announcements for seminar sessions they have missed. You are expected to view all pre-recorded lectures before the respective live sessions.

(2) Absenteeism

Absence from a live session without a valid reason will affect your overall course grade. Valid reasons include falling sick supported by a medical certificate and participation in NTU's approved activities supported by an excuse letter from the relevant bodies.

If you miss a live session, you must inform the course instructor via email prior to the start of the class.

Academic Integrity

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

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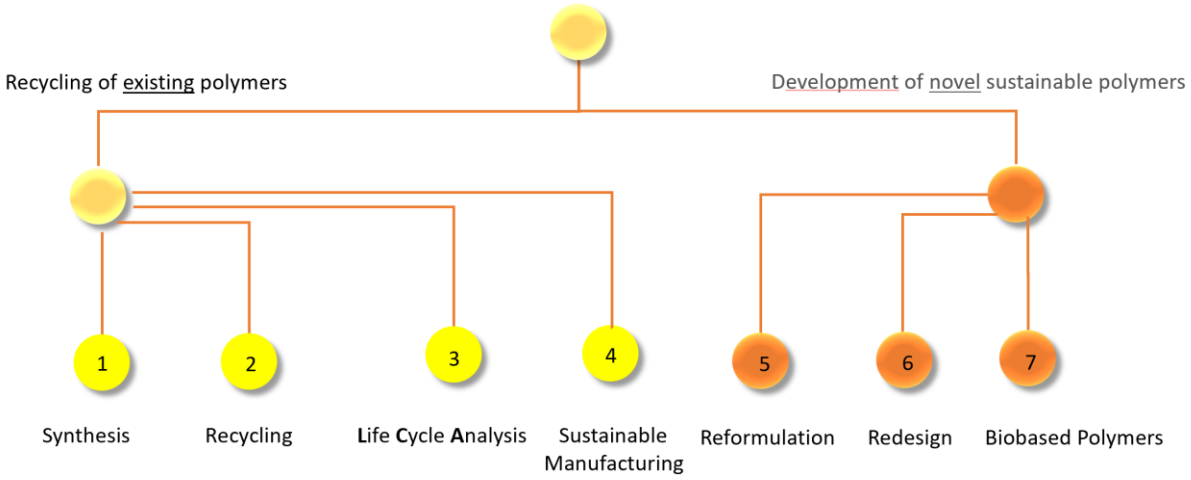

Course Instructor MS7460

Instructor	Office Location	Phone	Email
A.M. van Herk	NA	+31-643164333	a.m.v.herk@tue.nl

Planned Weekly Schedule (appr. 2 hours per week)

CA / videos	Topic	ILO	Readings/ Activities <u>before</u> respective session
Week 2 M1L1 *M1L2*	**Introductory meeting** Materials classification Key materials properties Step-growth polymerization	1, 2	Refresh knowledge on step-growth polymerization.
Week 3 M1L3 Modul 1	Chain-growth polym. (radical polymerization) Live session 1 (ILO 1,2) Quiz 1 (ILO 1, part of 2)	1, 2	Refresh knowledge on chain-growth polymerization.
Week 4 M1L3 *M2L1* *M2L2*	Chain-growth polym. (Ionic, Coord.) Environmental issues Collecting and sorting of materials. Primary recycling	2, 3, 4, 5	Read ref 7
Week 5 M2L3 Modul 2	Secondary/mechanical recycling with deterioration of properties and remedies Live session 2 (ILO 11) Quiz 2 (ILO 3,4,5,Pri, Sec)	3, 4, 5	Read ref 4
Week 6 M2L4	Tertiary/chemical recycling	5	Read ref 5

Week 7 M2L5	Quaternary recycling (energy recovery and/or compostable materials) Live session 3 (ILO 11) Quiz 3 (ILO 5)	5, 11	Read ref 24
Week 8 M3L1-L2-L3	Life Cycle Analysis	6	Read ref 14
Recess			
Week 9 M4L1-L2-L3	Aspects of sustainable manufacturing of materials, polymerization techniques. Live session 4 (ILO 11) Quiz 4 (ILO 6, 7)	7, 11	Read ref 17 and do a literature search on topic to be decided.
Week 10 *M5L1-L2-L3*	Reformulation of materials for increased sustainability -Monomaterials -Additives	8	Read selected paper from previous session (week 8)
Week 11 M6L1-L2	Redesign of materials on molecular level; Live session 5 (ILO 11) Quiz 5 (ILO 8, 9 L1 L2)	9, 11	Select you essay topic Read ref 19 and 20
Week 12 M6L3	Essay writing	9, 11, 12	Write essay before deadline.
Week 13 M7L1-L2-L3	Biobased building blocks Biobased materials replacements Live session 6 (ILO 11) Quiz 6 (ILO 9 L3, 10)	10	Read ref 23

Modul 3

Modul 4

Modul 5

Modul 6

Modul 7

Appendix 1

Quizzes

Criteria	Unsatisfactory: <40%	Borderline: 40% to 49%	Satisfactory: 50% to 69%	Very good: 70% to 89%	Exemplary: >90%
1 explain the important aspects of the polymerization mechanisms of materials	Lacks understanding of what a polymerization mechanism is. Cannot explain important aspects of polymerization mechanisms	Some understanding of what a polymerization mechanism is but cannot name them and only partially can mention important aspects.	Can classify the two main polymerization mechanisms but cannot name important aspects or only one.	Can classify the two main polymerization mechanisms and can name important aspects but misses out on one or two.	Can classify the two main polymerization mechanisms and can name all important aspects.
2 classify the main materials according to key materials properties and polymerization mechanism of formation.	Cannot mention any materials nor associate them with key materials properties. Is not able to match the materials with the polymerization mechanism of formation.	Can mention 3-4 different polymeric materials but cannot associate them with their key materials properties. Is only able to match one or two of the materials with the polymerization mechanism of formation.	Can mention 3-4 different polymeric materials and can at least for one material associate with their key materials properties. Is able to match most of the materials with the polymerization mechanism of formation.	Can mention 4 different polymeric materials and can associate the materials with most of their key materials properties. Is able to match most of the materials with the polymerization mechanism of formation.	Can mention 4 different polymeric materials and can associate with their key materials properties. Is able to match all the materials with the polymerization mechanism of formation.
3 identify the main environmental issues with polymer waste.	Does not recall any negative aspects of plastics in the environment.	Can mention one or two environmental issues but cannot give any further details.	Can mention most environmental issues but cannot give any further details.	Can mention most environmental issues and can give further details on one or two of them.	Can mention all environmental issues and can give detailed information about all of them.

4 identify the most important aspects of polymer waste collection and sorting.	Unable to identify any aspects of polymer waste collection nor polymer waste sorting.	Can identify some aspects of either polymer waste collection or sorting.	Can identify some aspects of polymer waste collection and sorting.	Can identify most aspects of polymer waste collection and sorting.	Can identify all aspects of polymer waste collection and sorting.
5 explain the main aspects and current industrial applications of the four polymer recycling routes	Is not aware of the four polymer recycling routes and cannot give any examples of industrial applications of polymer recycling routes.	Is aware of the four polymer recycling routes but not in any detail and cannot give any examples of industrial applications of polymer recycling routes.	Is aware of the four polymer recycling routes and can give most aspects of those routes and can give one or two examples of industrial applications of polymer recycling routes.	Is aware of the four polymer recycling routes and can give most aspects of those routes and can give examples of industrial applications of most of the four polymer recycling routes.	Is aware of the four polymer recycling routes and can give all aspects of those routes and can give examples of industrial applications of each of the four polymer recycling routes.
Criteria	**Unsatisfactory: <40%**	**Borderline: 40% to 49%**	**Satisfactory: 50% to 69%**	**Very good: 70% to 89%**	**Exemplary: >90%**
6 explain the main aspects of life cycle analysis	Unable to mention the foundations of LCA on polymers.	Able to comprehend one of the following aspects of LCA: raw material extraction, processing, manufacturing, use, re-use and disposal/recycling	Able to comprehend two of the following aspects of LCA: raw material extraction, processing, manufacturing, use, re-use and disposal/recycling	Able to comprehend most of the following aspects of LCA: raw material extraction, processing, manufacturing, use, re-use and disposal/recycling	Able to comprehend the following aspects of LCA: raw material extraction, processing, manufacturing, use, re-use and disposal/recycling
7 give examples of aspects of sustainable manufacturing of materials	Unable to mention any aspects of sustainable manufacturing. Is not aware of any aspects of emulsion polymerization.	Able to mention one or two aspects of sustainable manufacturing. Is not aware of any aspects of emulsion polymerization.	Able to mention one or two aspects of sustainable manufacturing. Is aware of some aspects of emulsion polymerization.	Able to mention most of the aspects of sustainable manufacturing. Is aware of main aspects of emulsion polymerization.	Able to mention the aspects of sustainable manufacturing. Is aware of all aspects of emulsion polymerization.
8 to apply aspects of reformulation of materials to make then more sustainable	Unable to read and understand materials science literature on formulations of materials. Unable to apply aspects of reformulation of materials to make them more sustainable.	Can read simple materials science literature and partially understand the formulation aspects. Can partially apply some aspects of reformulation of materials to make them more sustainable.	Can read simple materials science literature and understand the formulation aspects. Can partially apply some aspects of reformulation of materials to make them more sustainable.	Can read and understand materials science literature and understand the formulation aspects. Can partially apply some aspects of reformulation of materials to make them more sustainable.	Can read and understand materials science literature at a high level and understand the formulation aspects. Can apply complex aspects of reformulation of materials to make them more sustainable.

9 to apply aspects of redesigning materials on a molecular level to make them more sustainable	Unable to apply aspects of redesigning of materials on a molecular level to make them more sustainable.	Can read simple materials science literature and partially understand the molecular aspects. Can partially apply some aspects of redesigning of materials to make them more sustainable.	Can read simple materials science literature and understand the molecular aspects. Can partially apply some aspects of redesigning of materials to make them more sustainable.	Can read and understand materials science literature and understand the molecular aspects. Can fully apply some aspects of redesigning of materials to make them more sustainable.	Can read and understand materials science literature at a high level and understand the molecular aspects. Can apply complex aspects of redesigning of materials to make them more sustainable.
10 to explain the main biobased building blocks and biobased replacements of materials	Cannot mention any biobased building blocks and biobased replacement materials.	Can mention one or two biobased building blocks but cannot place them in the appropriate polymerization mechanism. Only can mention one or two biobased replacement materials. For neither of these can give further details on issues.	Can mention for each polymerization mechanism one or two biobased building blocks and can mention one or two biobased replacement materials. For neither of these can give further details on issues.	Can mention for each polymerization mechanism the main biobased building blocks and can mention multiple biobased replacement materials. Can also indicate some issues with using these.	Can mention for each polymerization mechanism the main biobased building blocks and associated challenges with using those building blocks and can mention multiple biobased replacement materials with their strengths and weaknesses.
11 critically read and interpret scientific literature in the area of sustainable polymeric materials	Unable to read and understand materials science literature in the area of sustainable polymeric materials.	Can read simple materials science literature and partially understand the sustainability aspects.	Can read simple materials science literature and understand the sustainability aspects.	Can read and understand materials science literature and understand the sustainability aspects.	Can read and understand materials science literature at a high level and understand the sustainability aspects very well.

Appendix 2

Class Participation (includes comprehension of scientific papers)

Standards	Criteria
A+ (Exceptional) A (Excellent)	Important contributions to class discussion; asks insightful questions; precisely answers questions; participates in a meaningful and constructive manner including enabling other students to contribute but does not dominate; demonstrates thoughtful ideas and opinions in a convincing manner.
A- (Very good) B+ (Good)	Meaningful contributions to class discussion; ask interesting questions; accurately answer the questions; capacity to articulate and present points of view clearly; participates in a meaningful and constructive manner; evidence of having read and assimilated the class material; Capable to demonstrate ideas and opinions in a convincing manner.
B (Average) B- (Satisfactory) C+ (Marginally satisfactory)	Some contributions to class discussion; ask some questions; some capacity to articulate and present points of view; some evidence of constructive engagement during discussion; Capable to demonstrate ideas and opinions.
C (Bordering unsatisfactory) C- (Unsatisfactory)	Minimal contributions to class discussion; ask very little questions; can answer a few questions; limited capacity to articulate and present points of view; limited evidence of constructive engagement during discussion.
D, F (Deeply unsatisfactory)	Very minimal or no contributions to class discussion; no questions; could not answer questions; no evidence of an individual viewpoint; failure to read the assigned reading; unexplained or unjustified absences from class activities.

Appendix 3

Essay (ILO 12)

Criteria	Unsatisfactory: <40%	Borderline: 40% to 49%	Satisfactory: 50% to 69%	Very good: 70% to 89%	Exemplary: >90%
<u>Comprehension</u> The ability to comprehend sustainability aspects of polymeric materials in	Unable to comprehend sustainability aspects of polymeric materials. Not "owning" the essay.	Partially comprehend some of the sustainability aspects of polymeric materials in relation to the topic of choice.	Comprehend some of the sustainability aspects of polymeric materials in relation to the topic of choice.	Comprehend most of the sustainability aspects of polymeric materials in relation to the topic of choice.	Comprehend the sustainability aspects of polymeric materials in relation to the topic of choice.

relation to the topic of choice.					
<u>Application</u> Ability to apply the relevant knowledge, principles and design aspects from the course on the topic of choice.	Unable to apply sustainability aspects of polymeric materials as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis. Not “owning” the essay.	apply a sustainability aspect of polymeric materials as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.	Can apply 2-3 aspects of sustainability aspects as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.	Can apply most of the sustainability aspects of polymeric materials as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.	Can apply all different aspects of sustainability in combination, as there are: reformulation, redesigning on molecular level, sustainably aspects during synthesis, collection and sorting, recycling, life cycle analysis.